Occupational Medicine & Health Affairs

Alchemy, Occup Med Health Aff 2020, 8:4

Research Article

Open Access

Verifying the Accuracy of Digital Goniometer Range of Motion Measurements

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Abstract

A goniometer is a device used to measure angles and is therefore useful in quantifying range of motion in athletic training and health-related fields such as physical therapy, orthopedic medicine, and occupational medicine. Various descriptions regarding the correct use of traditional goniometers exist in the literature.

Keywords: Goniometer; Machine learning; Smartphone; Telemedicine

Introduction

In recent years, smartphone apps have been developed to replace traditional goniometers. These goniometer applications use the smartphones' accelerometers to measure angles. One 2014 study [1,2] compared the measurements between a smartphone goniometer app and a traditional goniometer by measuring the range of motion of the knees of 36 volunteers performing three standing lunges. No significant difference was found between the measurements obtained using the smartphone goniometer and the universal goniometer.

Here, we take our standard for a "significant" difference between two measurements in clinical practice from the *AMA Guides to the Evaluation of Permanent Impairment, Fifth Edition*(hereafter referred to as the *AMA Guides*),which is a widely used standard in the United States for determining patients' impairment in workers' compensation and disability claims. When measuring the range of motion of patients' joints, the *AMA Guides*allows for a difference between two angle measurements of up to 10%; therefore, any difference in two measurements greater than 10% is considered a "significant" difference in this context [3].

The smartphone application used in this study is the RateFast Goniometer app, which has two modes of operation [4]. One is the default haptic mode, useful for measuring angles in-person, as was done in the 2014 study mentioned above. The other mode is the camera mode, which can beused for measuring angles for analysis by a remote diagnostician, such as in telemedicine.

To date, little evidence exists in the literature that confirms the accuracy of data obtained using a goniometer in a telemedicine setting. One study describes the accuracy of a traditional goniometer [5-7]. Another publication verified the use of machine learning software for measuring the range of motion of a patient's shoulder in telemedicine [7]. A third publication, in which elbow flexion and extension was measured, found that telemedicine-based goniometry is possible [8]. Although there has been little work done involving range of motion measurements in telemedicine, many studies demonstrate the validity of telemedicine in general. One study examining 200 patients for various issues compared the results from face-to-face consultations to telemedicine consultations and found no significant difference [9]. Several other publications discuss the efficacy of telemedicine in greater detail [10-25].

For many disability and workers' compensation claims, range of motion measurements are a critical factor to determine the level of a patient's impairment. As many patients do not have easy access to a physician's office—such as patients living in rural areas, or patients living far away from an in-network physician who accepts workers' compensation cases a physician's ability to measure a patient's range of motion from a remote location is a valuable tool in clinical practice. To test the accuracy of measuring a patient's range of motion remotely, a concomitant study used the Rate Fast Goniometer app in both haptic and camera modes to determine range of motion for flexion and extension for healthy individuals between the ages of 18-24 years [6]. Data from these experiments are described in the results of the current study.

Method

Three separate experiments were conducted to determine the accuracy of the measurements obtained using the RateFast Goniometer app in both in-person and telemedicine clinical settings. Prior to taking measurements for this study, three student researchers underwent training in the use of the Rate Fast Goniometer app by watching a RateFast educational video featuring a Qualified Medical Evaluator demonstrating the correct operation of the RateFast Goniometer app [4].The smartphone models used in all three experiments were either the iPhone 8 Plus or the iPhone X, each running version 1.3 of the RateFast Goniometer app.

The first experiment tested the accuracy of the RateFast Goniometer app when measuring verified angles on a flat surface. A fluid carpenter's level was used to draw a horizontal line on a whiteboard. Additional lines were drawn using a protractor creating angles of 0, 30, 45, 60, 90, 120, 135, 150, and 180 degrees. One student researcher then measured each angle twice using his or her own smartphone with the Rate Fast Goniometer app. Then, to account for variance among users and devices, the student researcher proceeded to use the Rate Fast Goniometer app with the other student researchers' smartphones to measure the same angles again. The remaining two student researchers did the same, with results shown in (Figure 1).

Experiment two was designed to expand upon the results obtained in the first experiment. One researcher drew random lines and measured the angle of each line using a protractor. The other two

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Received July 30, 2020; **Accepted** September 10, 2020; **Published** September 17, 2020

Citation: Alchemy J (2020) Verifying the Accuracy of Digital Goniometer Range of Motion Measurements. Occup Med Health Aff 8: 315.

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Phone Used	Angles on Protractor Screen to be Measured (degrees)	Angles (degrees) / Two Trials and Deviation / Person Taking Measurements: Evaluator 1					Evaluator 2					Evaluator 3					
	θ_0	θ_1	θ_2	$\theta_1-\theta_0$	$\theta_2-\theta_0$	$\theta_2-\theta_1$	θ_1	θ_2	$\theta_1-\theta_0$	$\theta_2-\theta_0$	$\theta_2-\theta_1$	θ_1	θ_2	$\theta_1-\theta_0$	$\theta_2-\theta_0$	$\theta_2-\theta_1$	$(\theta_2-\theta_1)_{avg}$
Phone 1	0	-1	0	-1	0	1	-1	-1	-1	-1	0	0	-1	0	-1	-1	0.0
	30	30	30	0	0	0	30	30	0	0	0	30	30	0	0	0	0.0
	45	44	44	-1	-1	0	44	44	-1	-1	0	44	45	-1	0	1	0.3
	60	60	60	0	0	0	60	59	0	-1	-1	60	60	0	0	0	-0.3
	90	90	90	0	0	0	90	90	0	0	0	90	90	0	0	0	0.0
	120	119	119	-1	-1	0	119	120	-1	0	1	120	120	0	0	0	0.3
	135	134	134	-1	-1	0	134	134	-1	-1	0	135	134	0	-1	-1	-0.3
	150	147	148	-3	-2	1	147	147	-3	-3	0	149	149	-1	-1	0	0.3
	180	179	180	-1	0	1	179	179	-1	-1	0	180	180	0	0	0	0.3
Phone 2	0	0	-1	0	-1	-1	0	-1	0	-1	-1	0	0	0	0	0	-0.7
	30	30	31	0	1	1	30	30	0	0	0	30	30	0	0	0	0.3
	45	44	45	-1	0	1	45	44	0	-1	-1	45	44	0	-1	-1	-0.3
	60	60	60	0	0	0	60	60	0	0	0	60	60	0	0	0	0.0
	90	91	90	1	0	-1	91	90	1	0	-1	90	90	0	0	0	-0.7
	120	120	120	0	0	0	120	121	0	1	1	120	121	0	1	1	0.7
	135	134	134	-1	-1	0	135	136	0	1	1	135	135	0	0	0	0.3
	150	149	149	-1	-1	0	149	148	-1	-2	-1	149	150	-1	0	1	0.0
	180	180	180	0	0	0	179	180	-1	0	1	180	180	0	0	0	0.3
Phone 3	0	-1	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0.3
	30	30	30	0	0	0	30	30	0	0	0	30	30	0	0	0	0.0
	45	45	44	0	-1	-1	44	45	-1	0	1	45	45	0	0	0	0.0
	60	60	60	0	0	0	60	60	0	0	0	60	60	0	0	0	0.0
	90	90	90	0	0	0	90	91	0	1	1	90	90	0	0	0	0.3
	120	119	120	-1	0	1	120	120	0	0	0	120	120	0	0	0	0.3
	135	135	135	0	0	0	135	135	0	0	0	135	135	0	0	0	0.0
	150	149	148	-1	-2	-1	149	149	-1	-1	0	149	149	-1	-1	0	-0.3
	180	179	180	-1	0	1	180	180	0	0	0	180	180	0	0	0	0.3
			mean	-0.5	-0.4	0.1			-0.4	-0.4	0.0			-0.1	-0.1	0.0	0.1
			std.dev.	0.8	0.7	0.7			0.7	0.9	0.6			0.4	0.5	0.5	0.3

Figure 1: Angle measurements using the RateFast app for angles drawn on a whiteboard with a protractor. Each student made two measurements (θ1&θ2) of each angle drawn (θ0) using each of the three smart phones.

researchers separately used the RateFast Goniometer app to measure the angles. To limit bias, each of the three measurements was made without the researcher knowing the results of the measurements taken with the other tool. The results obtained using the goniometer were then compared to the reference values obtained using the protractor, as shown in (Figure 2).

The third and final experiment was designed to verify the accuracy of the RateFast Goniometer app when measuring the range of motion of patients in both in-person and telemedicine clinical settings. 53 volunteers were gathered from the Hamline University community for the purpose of testing the accuracy of the Rate-Fast Goniometerapp and, in a separate experiment [5], performing shoulder range of motion studies with and without a TheraBand (an elastic band to measure strength-testing or for use in physical therapy).Although the TheraBand and other factors affecting shoulder range of motion are not the focus of this paper, the need for sufficient data to investigate such dependences and additional clinical variables would provide several hundred measurements that can be used to statistically verify the accuracy of the RateFast Goniometer app.

In this third experiment, the RateFast Goniometer app was used to measure the flexion and extension in the sagittal plane of each volunteer's shoulder, which involves measuring the angle formed by the volunteer's arm and the torso (the torso serves as the 0° plane of reference).The arm was extended forward with the elbow fully extended and the thumb pointed upward. This is the method of flexion and extension measurement specified by the *AMA Guides* [3].

Before beginning the measurements, each volunteer was asked to do two sets of flexion and extension warm-up stretches.Data collection began with the volunteer reaching the terminal angle of the arm in both flexion and extension twice for each arm, first with and then without the Thera Band resistance device, for a total of 16 angle measurements. With the volunteer's arm at the terminal angle of flexion or extension, the angle was measured in haptic-mode by placing the smartphone running the RateFast Goniometer app on the mid-bicep and the elbow while at the terminal flexion or extension. (Figures 3 and 4) An attempt was made to perform the experiment with the smartphone strapped to the arm, but it was observed that the goniometer rotation axis did not remain perpendicular to the sagittal plane both in flexion and extension (i.e., rotated away from horizontal). Therefore, the measurements were taken using the goniometer after the terminal angle was reached.

For the camera mode measurements, a picture was taken using a second smartphone on a tripod, and a third smartphone was used to obtain videos of the measurement-taking process. The second smart phone (used for pictures) was positioned at a distance of 12 feet from the volunteer, which safely allowed the camera to capture the entire volunteer with his or her arm fully extended, and at a height aligned with the volunteer's shoulder to minimize parallax issues.

The camera was positioned at the volunteer's shoulder height because it was determined that parallax contributed insignificantly if the camera was positioned at a height no lower than the waist and no higher than the head. The test to determine the contribution of parallax on angle measurements was performed by altering the height of the camera while measuring the angle at which a student researcher held their arm. The arm of the student researcher was placed against a poster board with lines drawn at 10 degree increments above and below the horizon, thereby determining the angle at which the arm was held. The camera was placed 12 feet away from the subject's shoulder and initially set at the same height of the shoulder. The camera was then raised and lowered at 1-inch increments with a picture taken at

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Angles (degrees)					
θ_0	θ_1	θ_2	$\theta_1 - \theta_0$	$\theta_2 - \theta_0$	$\theta_2 - \theta_1$
10	9	9	-1	-1	0
26	26	27	0	1	1
50	47	50	-3	0	3
71	69	69	-2	-2	0
99	98	98	-1	-1	0
15	13	12	-2	-3	-1
29	24	27	-5	-2	3
42	40	41	-2	-1	1
78	77	76	-1	-2	-1
95	93	94	-2	-1	1
25	23	25	-2	0	2
41	40	42	-1	1	2
56	55	57	-1	1	2
77	74	75	-3	-2	1
110	108	109	-2	-1	1
35	35	34	0	-1	-1
63	62	62	-1	-1	0
93	92	92	-1	-1	0
115	112	112	-3	-3	0
129	127	126	-2	-3	-1
22	22	21	0	-1	-1
37	37	36	0	-1	-1
56	56	56	0	0	0
86	86	86	0	0	0
102	100	102	-2	0	2
8	8	10	0	2	2
40	38	39	-2	-1	1
73	72	74	-1	1	2
106	110	108	4	2	-2
130	132	129	2	-1	-3
		mean	-1.1	-0.7	0.4
		std.dev.	1.6	1.3	1.5

Figure 2: Angle measurements using the RateFast app for random angles drawn on a whiteboard.Each angle was measured with a protractor (θ0) by one student researcher, then independently measured by two other student researchers (angles labeled θ1 and θ2).

Figure 3: Flexion (left) and extension (right) in the sagittal plane.

Figure 4: Using the RateFast Goniometer app in (left) "haptic mode" to take in-person measurements, and (right) "camera mode"to take telemedicine measurements.

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MAXIMUM ANGLE OBTAINED (DEG)				Haptic vs. Camera (Females)																											mean	st.dev.
NO BAND	MAJOR	FLEX	Haptic	85	84	89	76	112	69	68	90	76	75	83	106	82	110	81	95	84	96	90	99	82	90	102	82	103	74	95	88.1	
			Camera	74	82	90	78	111	71	72	90	80	78	85	107	82	114	81	95	85	104	91	96	83	86	100	81	100	71	89	88.0	
			Difference (1-2)	11	2	-1	-2	1	-2	-4	0	-4	-3	-2	-1	0	-4	0	0	-1	-8	-1	3	-1	4	2	1	3	3	6	0.1	3.7
		EXT	Haptic	130	136	144	148	136	170	137	139	148	138	148	159	135	150	149	138	136	150	154	174	143	137	133	162	144	147	146	145.6	
			Camera	128	138	146	143	135	163	134	141	138	128	147	159	126	145	143	130	126	148	155	167	137	138	128	165	137	139	136	141.5	
			Difference (1-2)	2	-2	-2	5	1	7	3	-2	10	10	1	0	9	5	6	8	10	2	-1	7	6	-1	5	-3	7	8	10	4.1	4.3
	MINOR	FLEX	Haptic	94	93	90	84	107	93	75	96	82	86	85	105	90	101	77	108	87	95	88	96	92	93	90	83	104	78	102	91.6	
			Camera	94	90	90	84	107	93	70	97	85	83	86	105	90	99	75	113	87	95	88	96	92	94	90	83	97	78	102	91.2	
			Difference (1-2)	0	3	0	0	0	0	5	-1	-3	3	-1	0	0	2	2	-5	0	0	0	0	0	-1	0	0	7	0	0	0.4	2.3
		EXT	Haptic	134	125	133	137	127	174	124	135	148	132	145	163	137	150	146	134	136	150	150	170	137	137	133	162	144	147	146	142.8	
			Camera	138	130	132	129	133	168	123	134	148	128	145	160	128	143	133	133	121	147	151	163	140	127	129	152	139	140	145	139.2	
			Difference (1-2)	-4	-5	1	8	-6	6	1	1	0	4	0	3	9	7	13	1	15	3	-1	7	-3	10	4	10	5	7	1	3.6	5.3
BAND	MAJOR	FLEX	Haptic	71	84	75	75	100	77	65	90	70	74	81	108	80	98	78	80	77	83	80	100	79	89	98	83	100	67	96	83.6	
			Camera	87	82	78	79	90	77	65	87	75	71	85	106	77	104	85	86	82	95	83	101	81	87	100	80	94	69	98	85.3	
			Difference (1-2)	-16	2	-3	-4	10	0	0	3	-5	3	-4	2	3	-6	-7	-6	-5	-12	-3	-1	-2	2	-2	3	6	-2	-2	-1.7	5.3
		EXT	Haptic	125	140	129	144	132	167	125	130	134	131	139	146	122	139	135	131	129	139	142	180	140	136	113	146	137	135	135	137.1	
			Camera	118	139	139	143	123	167	118	132	129	115	138	150	125	143	129	124	129	144	138	175	140	136	115	148	136	135	129	135.4	
			Difference (1-2)	7	1	-10	1	9	0	7	-2	5	16	1	-4	-3	-4	6	7	0	-5	4	5	0	0	-2	-2	1	0	6	1.6	5.3
	MINOR	FLEX	Haptic	79	92	78	101	105	91	73	97	80	81	83	110	80	90	72	88	95	85	89	91	94	92	88	80	101	68	95	88.1	
			Camera	90	86	79	91	110	90	70	95	80	83	70	98	87	84	71	88	104	89	84	91	93	91	89	79	101	68	100	87.4	
			Difference (1-2)	-11	6	-1	10	-5	1	3	2	0	-2	13	12	-7	6	1	0	-9	-4	5	0	1	1	-1	1	0	0	-5	0.6	5.7
		EXT	Haptic	125	121	120	136	124	172	121	117	134	117	146	145	128	144	123	135	137	146	138	170	139	140	132	165	127	137	143	136.4	
			Camera	129	126	120	131	130	169	122	115	135	119	147	136	112	141	121	129	131	145	135	165	143	135	124	160	115	129	142	133.6	
			Difference (1-2)	-4	-5	0	5	-6	3	-1	2	-1	-2	-1	9	16	3	2	6	6	1	3	5	-4	5	8	5	12	8	1	2.8	5.2
																													Overall Mean Values (Female)	Flexion:	-0.1	4.2
																														Extension:	3.0	5.0
																														Both:	1.4	4.6

MAXIMUM ANGLE OBTAINED (DEG)				Haptic vs. Camera (Males)																										mean	st.dev.
NO BAND	MAJOR	FLEX	Haptic	89	82	73	93	120	92	95	103	87	94	90	104	85	98	92	91	73	108	109	96	94	78	82	85	90	81	91.7	
			Camera	82	89	79	88	119	103	98	100	87	94	90	104	85	97	90	88	72	106	106	94	90	74	82	83	89	78	91.0	
			Difference (1-2)	7	-7	-6	5	1	-11	-3	3	0	0	0	0	0	1	2	3	1	2	3	2	4	4	0	2	1	3	0.7	3.8
		EXT	Haptic	155	125	140	149	150	145	146	159	136	140	130	135	142	160	146	148	118	125	150	132	153	130	135	146	142	127	140.9	
			Camera	155	132	137	154	128	137	147	160	131	136	127	138	137	149	148	131	111	128	151	134	150	134	121	146	156	129	138.7	
			Difference (1-2)	0	-7	3	-5	22	8	-1	-1	5	4	3	-3	5	11	-2	17	7	-3	-1	-2	3	-4	14	0	-14	-2	2.2	7.7
	MINOR	FLEX	Haptic	82	77	79	89	125	107	100	98	92	95	85	91	83	98	88	90	75	104	103	87	95	81	92	82	95	90	91.7	
			Camera	82	86	79	89	125	107	103	98	91	96	90	90	80	98	85	90	75	104	103	87	95	80	92	85	95	90	92.1	
			Difference (1-2)	0	-9	0	0	0	0	-3	0	1	-1	-5	1	3	0	3	0	0	0	0	0	0	1	0	-3	0	0	-0.5	2.4
		EXT	Haptic	155	125	140	152	150	145	151	139	136	140	132	135	142	160	146	148	120	127	154	121	160	130	141	147	143	129	141.1	
			Camera	146	118	142	145	142	141	147	137	135	137	127	123	136	152	137	146	122	122	155	115	145	125	130	142	153	129	136.5	
			Difference (1-2)	9	7	-2	7	8	4	4	2	1	3	5	12	6	8	9	2	-2	5	-1	6	15	5	11	5	-10	0	4.6	5.2
BAND	MAJOR	FLEX	Haptic	89	86	68	80	120	94	84	94	78	94	77	92	85	95	95	88	72	107	104	93	93	72	82	88	78	84	88.2	
			Camera	87	81	73	77	117	103	86	100	77	93	90	91	80	94	95	85	77	105	100	90	93	72	85	89	69	89	88.4	
			Difference (1-2)	2	5	-5	3	3	-9	-2	-6	1	1	-13	1	5	1	0	3	-5	2	4	3	0	0	-3	-1	9	-5	-0.2	4.8
		EXT	Haptic	150	120	136	144	138	138	140	144	135	125	117	127	136	146	149	133	121	128	133	137	150	124	114	140	130	123	133.8	
			Camera	148	123	141	148	142	142	141	147	127	130	120	122	132	150	153	135	122	127	131	138	143	129	114	143	133	128	135.0	
			Difference (1-2)	2	-3	-5	-4	-4	-4	-1	-3	8	-5	-3	5	4	-4	-4	-2	-1	1	2	-1	7	-5	0	-3	-3	-5	-1.2	3.8
	MINOR	FLEX	Haptic	82	88	72	87	115	94	99	97	83	94	84	88	79	96	88	82	73	103	94	85	97	77	90	84	81	85	88.3	
			Camera	79	91	72	84	114	102	102	103	84	92	82	90	76	85	88	86	70	102	96	87	92	74	90	85	90	89	88.7	
			Difference (1-2)	3	-3	0	3	1	-8	-3	-6	-1	2	2	-2	3	11	0	-4	3	1	-2	-2	5	3	0	-1	-9	-4	-0.3	4.2
		EXT	Haptic	147	125	139	152	130	137	147	140	137	125	131	120	135	159	138	143	114	125	140	125	138	125	130	145	136	136	135.3	
			Camera	139	117	130	148	127	130	147	139	132	127	128	120	129	147	134	143	114	120	145	122	133	128	122	146	144	138	132.7	
			Difference (1-2)	8	8	9	4	3	7	0	1	5	-2	3	0	6	12	4	0	0	5	-5	3	5	-3	8	-1	-8	-2	2.7	4.7
																												Overall Mean Values (Male)	Flexion:	-0.1	3.8
																													Extension:	2.1	5.3
																													Both:	1.0	4.6
																												Overall Mean Values (All Volunteers)	Flexion:	-0.1	4.0
																													Extension:	2.6	5.3
																													Both:	1.2	4.7

Figure 5: Angle measurements from volunteer study illustrating haptic (in-person) data compared to camera (telemedicine) data.

each height. The angle of the arm in each picture was then measured using the RateFast Goniometer app in camera mode. The Rate Fast Goniometer app camera mode measurements were then compared to the known angle of the arm. The difference between the known angle and the measurements obtained from the picture using the Rate Fast Goniometer app only became significant once the camera height fell below the subject's waist or rose above their head.

Once all 16 measurements were taken, the angles were re-measured by analyzing the pictures on a computer screen using the camera function on the RateFast Goniometer (see right side of Figure 4).This was done to measure the reliability of the measurements obtained using the camera mode of the RateFast Goniometer app in a telemedicine scenario, such as a medical practitioner measuring the image of a patient on a computer screen. The result for this experiment can be seen in (Figure 5).

Results

The results of the first experiment, with three student researchers using three different smartphones to measure nine different known angles, are shown in (Figure 3).Across the three student researchers and the three smartphones, the average difference between measurements was 0.6° and the average standard deviation was 0.3°.(All values have been rounded to the nearest tenth.).

The results of the second experiment, where angles were drawn at random on a whiteboard and measured using both a protractor and the RateFast Goniometer, are shown in (Figure 4).

In (Figure 4), the mean values in columns 4 & 5 (-1.1° and -0.7°, respectively) show that the angles measured with the RateFast goniometer are less than those measured with aprotractor, averaging to a difference of 0.9°.The mean value in column 6 demonstrates that angle measurements by two separate individuals using the RateFast Goniometer app are 0.4° on average. The standard deviations average to 1.5°.

The results for the measurements of the maximum angles obtained in the third experiment are shown in (Figure 1), with results for females shown in (Figure 5A) and results for males shown in (Figure 5B).As mentioned previously, the data was obtained from the study [5] in which the 53 volunteers (27 females and 26 males) checked their range of motion both with and without using a Thera Band; hence, (Figure 5) divides results into "band" and "no band" categories. The categories "major" and "minor" refer the volunteer using the "dominant" or "non-dominant" arm, respectively. Finally, both flexion and extension values were measured, as illustrated previously in (Figures 3 and 4). No significant difference is seen when comparing the data for males vs. females, major vs. minor arms, or Theraband vs. no Theraband. (Figure 1) shows the range of motion data for the 53 volunteers, as well as the mean for each measurement category. The haptic mode measurements and the camera mode measurements have an average difference of 1.2° and the standard deviation of the *difference* between haptic and camera measurements was determined to be4.7° across all volunteers.

Discussion

When testing the accuracy of the measurements obtained by the Rate Fast Goniometer app, a practical definition of "accuracy" must be agreed upon. Given the widespread use and practical application of the *AMA Guides*, we have adopted the functional definition of "accuracy" found in this text. As mentioned, when evaluating the accuracy of a set of measurements, the *AMA Guides* tolerates deviation between two measurements of up to 10% [3].Within the context of the shoulder flexion plane, we consider 180° to be 100% range of motion; in other words, an individual with a healthy shoulder can be expected to move their shoulder along the flexion plane to 180°. For the shoulder's extension plane, 40° is considered 100% range of motion. Therefore, to be considered "accurate, "two flexion measurements must be within 18° of each other (10% of 180° is 18°) while two extension measurements must be within 4°of each other (10% of 40° is 4°).

When applying the *AMA Guides*' standard of accuracy to the first experiment of this study, we find that the measurements obtained by the Rate Fast Goniometer app are accurate; the results fall within the error tolerance of 10%.

In the results from the first experiment (Figure 1) the average difference between measurements was 0.6° and the average standard deviation was 0.3°, which are well beneath the error-tolerance of 18° for flexion or 4° for extension defined by the *AMA Guides*.

Similarly, in the second experiment (Figure 2, columns 4, 5, and 6) the mean values (under 1°) and the standard deviation values (averaging to 1.5°) of the results are within the acceptable range of accuracy defined by the *AMA Guides* for both flexion and extension shoulder planes.

In the third experiment, the in-person measurements obtained using the haptic mode of the Rate Fast Goniometer app can be seen to deviate slightly in most cases, but on average are consistent with the camera measurements obtained using the Rate Fast Goniometer app on a computer screen while viewing the pictures taken while the measurements were made. The haptic and camera measurements are, on average, within 1.4° of each other, which is well within 18° for the flexion plane and 4° for the extension plane.

Conclusion

From our results, we can conclude that the Rate Fast Goniometer app can be used to accurately measure angles according to the standards of accuracy set forth in the *AMA Guides*. Given the minor deviation in results between the haptic mode and the camera mode of the Rate Fast Goniometer app, this digital goniometer application may be used to obtain accurate measurements both in telemedicine settings as well as in a doctor's office.

Acknowledgements

We thank Sarah Alchemy (University of Puget Sound) for assistance in the determination of the calibration of the video goniometer for the study; we thank Chris Young PhD (Alverno College) for assistance in revising the paper; we thank the Honorable Steven Siemers for reviewing the discussion of the medical-legal implications of the study's results; we thank the 53 volunteers from the Hamline University student body. This research was funded by the Hamline University Kent H. Bracewell Scholarship Fund and the Barbara Lund Fund.

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